STRONG UPPER OCEAN COOLING DUE TO THE STIR OF PHET SUPER CYCLONE

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ABSTRACT

Arabian Sea is more vulnerable to cyclonic systems during the recent decades, the intensity (cat 4 or 5) of cyclone systems are increased due to the effect of global warming. It is essential to study the upper ocean changes during the cyclone period. In the present study focuses on the upper ocean changes during the Phet super cyclone (31 May – 7 June 2010). Multi satellite data provide inimitable opportunity to explore upper ocean rejoinders along the long track of major super cyclonic storm Phet. Two large areas of maximizing upwelling and surface cooling (2 – 6°C) are observed along the track. The first cooling area is looks like a cold tongue and it is approximately 350 km. This is a unique feature and also first time observed in the Arabian Sea. The mixed layer and the depth of 20°C isotherm are deepening 54 m and 2m respectively after the passage of Phet.

1. INTRODUCTION

Tropical cyclones seldom assault the Oman coast during summer and may change greatly the ocean conditions. They depend on the ocean for their energy supply. Observations have shown that the state of the ocean has a great influence on the intensities, structures and even paths of tropical cyclones (Fisher, 1958; Tisdale and Clapp, 1963; Perlroth, 1967 and Brand, 1971; Black, 1977; Chang and Anthes, 1979) and also capable of altering the upper layers of the ocean. The wind stress and pressure drop associated with tropical cyclone generated turbulent mixing in the ocean, generate ocean currents and alters the ocean's thermal structure. Subsurface water from a depth of 60 m has been upwelled to the surface, cooling the surface temperature 1-7°C and deepening of mixed layer after the passage of tropical cyclones (Black, 1983). The cooling of sea surface persists for about a week and it is observed at the right side of the storms track (Price et al. 1996, Jacob et al. 2000). This cooling is mainly due to the vertical turbulent mixing induced by the strong momentum flux into ocean currents and accompanied entrainment of cooler thermocline water into the upper mixed layer. Entrainment mixing in the mixed layer can be generated by the near-surface, wind-driven shear, convective overturning due to the surface buoyancy fluxes and velocity shear at the mixed layer base. The amount of SST cooling underneath a hurricane can significantly reduce the heat and moisture fluxes at ocean surface, which may play an important role in the storm evolution (Bender and Isaac 2000). The main objective of this study is to appraise the upper ocean changes after the passage of severe cyclonic storm (phet) in the Arabian Sea.

2. DATA AND METHODOLOGY

2.1. Cyclone data

The cyclone track (Fig 1) data used in this study were available from the India Meteorological Department (www.imd.gov.in) and Unisys Weather Web site (http://weather.unisys.com), which is based on the best hurricane track data issued from the Joint Typhoon Warning Center (JTWC). The data include the maximum sustained surface wind speed and the location of the cyclone center every 6 hours during 31 May – 7 June 2010.

2.2. Satellite data

The following satellite products are used in the present study. The merged microwave product of daily sea surface temperature with a spatial resolution of 25 km was acquired based on Tropical Rain Measuring Mission (TRMM) Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer–EOS (AMSRE). These two satellites have together can overcome influence of cloudy conditions during cyclones (Wentz et al., 2000). Therefore, this product can provide continuous SST observations with a better resolution before, during and after a cyclone. This data product is produced and distributed by Remote Sensing Systems (www.remss.com).

2.3. Sea Surface Winds

Daily ocean surface wind vector from the Advanced Scatterometer (ASCAT) at a spatial resolution of 12.5 km (along) X 12.5 (across) is obtained from http://podaac.jpl.nasa.gov/oceanwind/Metop-A (Verspeek et al., 2009). It is an improved follow-on to ESA's ERS-1 and ERS-2 scatterometer missions. Transmitting at of 5.255 GHz (C-band), six antennas provide twice the coverage of a single ERS scatterometer using a dual-swath fan-beam configuration.

2.4. In-situ observations (Argo)

Nearly more than 650 profiling floats has launched since 2000 in the Indian Ocean under International Argo program. They record temperature and salinity between the surface and 1000~2000 m every 10 days. In this study I utilize the profile data during 31-7 June 2010 (Fig 1) from the Indian National Centre for Ocean Information Services (INCOIS). Mixed Layer Depth is estimated using Kara et al., 2003 criteria.

2.5. Methodology

Ekman pumping velocity (EPV) and Ekman layer depth (D) is computed from ASCAT wind fields (Stewart, 2007). Time series of sea surface temperature, wind speed, EPV and D were obtained by averaging daily data averaged over the four boxes (A, B, C & D). Along track scale and Rossby number is calculated by using Price et al., (1994) equations.

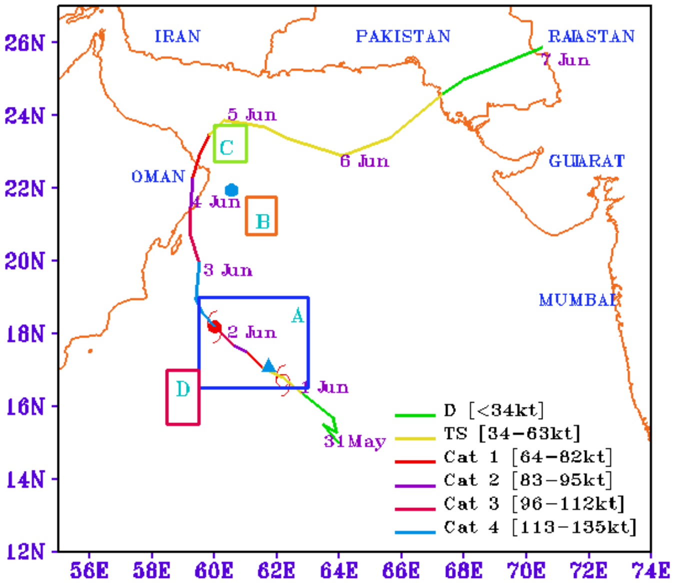

Figure 1. Different stages of Phet severe cyclone (31 May – 7 June 2010) with hurricane intensity and its track. The color scale is given according to the Saffir-Simpson scale based on wind speed. Symbols (triangle & Circle) represent position of Argo floats. Cooling areas are represent four boxes A (500 km²), B (200km²), C (150km²) and D (150 km²).

3. RESULTS AND DISCUSSIONS

The deed of a tropical cyclone is predisposed by a number of factors, one of which is the sea surface temperature parameter. A conspicuous negative correlation (-0.51) is observed between central sea level pressure and sea surface temperature along the track of Phet cyclone. It indicates that SST values and the time required for a tropical depression to attain intense tropical cyclone (category 4 or 5). That is, the higher the sea surface temperature, the shorter the time required for the category 1 to 5 on Saffir-Simpson scale. The same type of feature is observed in the North Atlantic Ocean during Hurricane Esther (Perlroth, 1962). Phet Cyclone is formed in the central Arabian Sea where the ocean temperatures are warm (> 29°C). The system then pursue a strap of warm water west northwest for few days and reached maximum intensity (Cat 4) during 2nd June 2010 with wind speed of 125 knts. It moved with the same intensity toward the Oman. After reaching the land its intensity is slightly decreased (Cat 2), but the SST is still warming (29°C) at the right side of the track (off Oman coast). This warming (Fig 2a) gives fuel to maintain its intensity even though it is on the land surface. In the same day (4 June) it moved northward direction toward warmer water, and then continued to follow the warmest water toward the northeast. Again it travels in the eastward direction and crossed the Pakistan coast. Aside from this odd change in path which occurred as the cyclone neared significantly colder water, another feature of considerable interest us the pool of decidedly cold water which formed behind the cyclone on the 7th June (Fig 2b).

Three cooling patches are observed in and around the cyclone track after its passage. One is along the cyclone track, second one is e right side of the track, off the Oman coast and the last one is left side of the cyclone track. The surface cooling along the track is near 6°C, whereas 4°C off Oman coast and 2-3°C at left side of the track. From all the three patches, along the track area is like a cold tongue (Fig 2b). The appearance of cold water behind the cyclone is apparently due to the upwelling of colder water. Tropical cyclones not only pretentious directly by the surface temperature but could be affected indirectly by the cold water brought from the subsurface to the surface by upwelling and mixing stimulated by cyclone's winds.

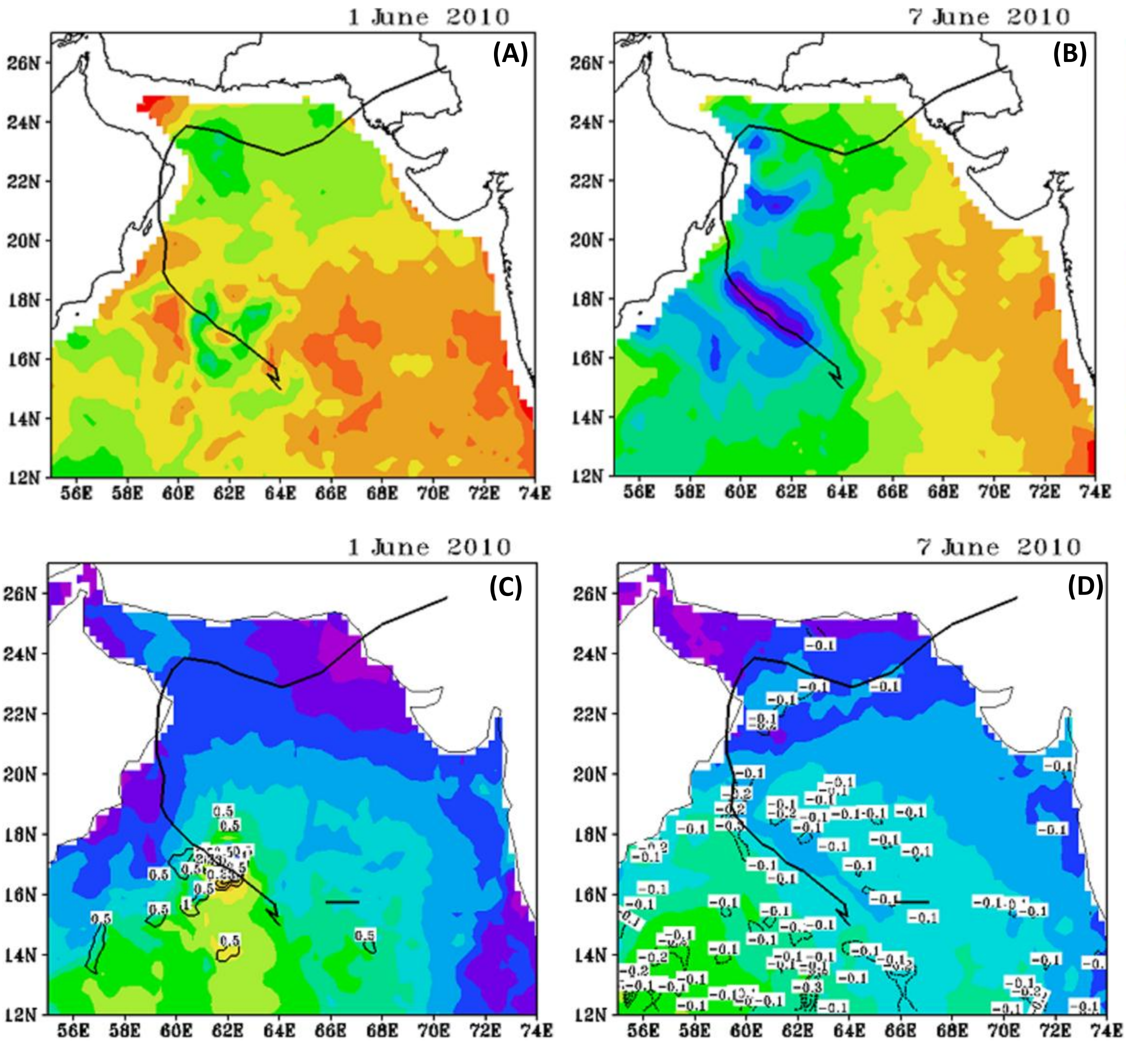

Figure 2. Changes in sea surface temperature (A&B), Ekman Pumping Velocity (contours x10^{-4} m/s) and Ekman Layer Depth (shaded) before and after the cyclone passage.

Upwelling conditions are revealed by EPVS shown in Fig (2c&d). The EPV exhibits huge changes, it is weak (0.5x10^{-4} m/s) before cyclone phet (Fig 2c) it is coinciding the low wind speeds during that period and indicates weak upwelling or downwelling along the cyclone track region, but during cyclone period (cat 4) EPV (2x10^{-4} m/s) is strong (figure not shown) and winds are also reached high. After the passage of cyclone strong negative EPV (Fig 2 d) is observed along the track due to the strong wind stress curls, it is also looks like tongue shape. This strong curl is induced bring the upwelling of sea water from the deeper depths. Next the wind induced Ekman layer depth is calculated along the track. Before and during the cyclone period Ekman layer depth is deeper (270 – 355 m) shown in Fig (2c), but after the passage of Phet cyclone is drastically reached the surface layers (110-150 m). This indicates strong upwelling induced by the entrainment process.

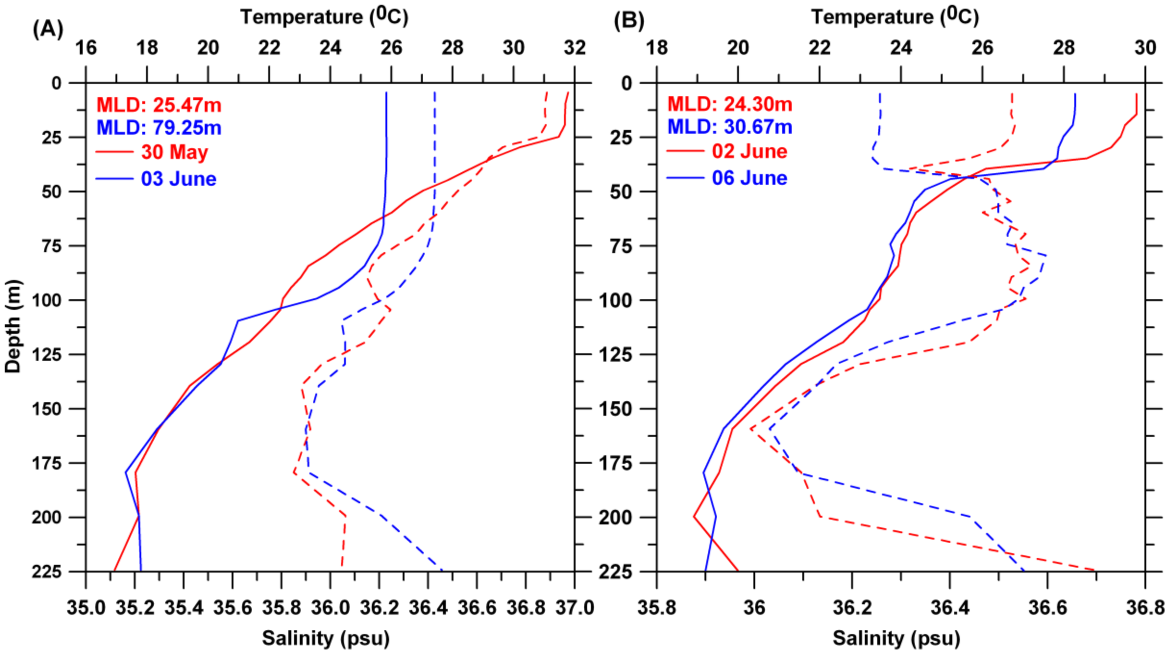

Figure 3. Vertical Profiles of Temperature and Salinity before and after the Phet Cyclone. A represent observations at Triangle and B at Circle in Fig 1. Red colour indicates before cyclone and blue is after the cyclone. Solid line represents Temperature and Dotted line represents salinity.

Vertical temperature and salinity profiles illustrated drastic amends before and after the Phet cyclone (Fig 3). The mixed layer depth (MLD) is thin, the depth of 26°C isotherm is high before the cyclone, but after its passage the scenario is upturned MLD is deepen (ΔMLD = 54m) and there is no 26° isotherm. The mixed layer kept cooling down attained the minima at around 30 May. Since the thermocline was superficial (Fig 2a) preceding to the passage of Phet cyclone, the deep water appeared to be upwelled to the surface near the cyclone centre. This upwelling phenomenon is also associated with strong mixed layer thickening, due to strong enhanced mixing and entrainment. The venting of thermocline also supports the SST cooling by upwelling. The surface mixed layer not only thickened significantly but also mixed efficiently due to strong turbulence produced by vigorous cyclone wind forcing. The thermocline became much thinner due to the upwelled thermocline in the deeper layer.

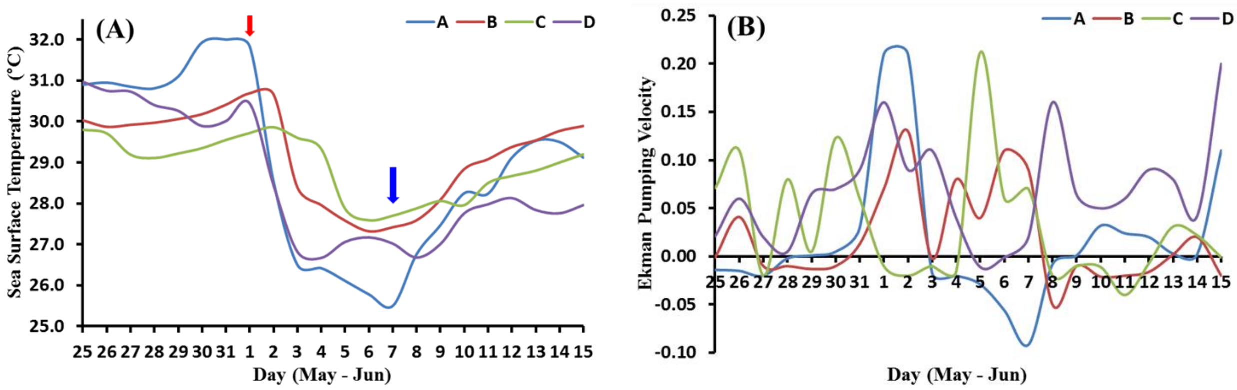

Figure 4. Time series of (A) Sea surface temperature (°C) and (B) Ekman pumping velocity (10^{-4} m/s) at four boxes represented in Fig 1 during 25 May to 15 June 2010. Red and blue arrows represents the day of before and after the cyclone.

In order to quantitatively discuss the influence of Phet cyclone on upper ocean, time series of SST and EPV averaged at four boxes (Fig 1) before, during and after Phet and it is shown in Fig 4. Before the Phet SST is high

(32°C) represented with red arrow (Fig 4a), weak winds and low EPV is clearly observed. Winds become stronger (4 times high than the pre cyclone speed) along with increase in EPV and SST is falling rapidly during the Phet (Cat 1 to Cat 4) at box A and C, but the SST decrease is slow at B and D. After the passage of Phet strong cooling is seen at box A (6.23°C), but it is low at B & D (2.99°C) and EPV is also show the same pattern at these boxes. Sea surface temperature decrease is higher than the Gonu cyclone formed at this region during 2007 (Wang and Zhao, 2008). This is one of the causes for further intensification (Cat 4 to Cat 5) of Phet cyclone.

Table 1. Different upper ocean variables and scaling parameters at four boxes. Within brackets represents after the passage of Phet.

Parameter	A	B	C	D
Moving speed (U_h in m/s)	3.86	3.53	3.56	3.86
Range of U_h (m/s)	2.3 - 5.3	3.2 – 4.1	3.1- 3.9	2.3 - 5.3
Maximum sustained wind (MSW) in m/s	64	46	23	64
Mean MSW (m/s)	58	37	19	58
Mixed layer depth (m)	25 (79)	24 (31)	N/A	N/A
Mixed layer temperature (°C)	30.9 (25.89)	29 (28.25)	N/A	N/A
Mixed layer salinity (psu)	36.8 (36.4)	36.5 (36.2)	N/A	N/A
*Thermocline displacement (m)	13	4.5	3.4	7.1
*Along track scale (L_i) in km	87	67	62	94
*Rossby Number (Q)	0.1	0.02	N/A	N/A
Sea surface temperature (°C)	31.9 (25)	29.5 (26.28)	29.17 (26.43)	30.54 (26.52)
Ekman pumping velocity (10^{-4} m/s)	0.21 (-0.02)	0.07 (0.09)	-0.01 (0.07)	0.16 (0.02)
Ekman layer depth (m)	156 (128)	85 (68)	82 (91)	111 (161)

*Estimate parameter using Prices et al., 1994 equations.

The importance of upwelling has also been examined by Greatbatch (1985), who defined the parameter k, which is a ratio of the time over which upwelling takes place or f^{-1} to the time over which entrainment of deeper waters occurs or L_i/U_h. The along track scale of Phet cyclone is estimated as 87 km. Nondimensional parameter (k)for Phet cyclone is 1.0. This implies that since Phet is a moderate slow moving cyclone, upwelling of water can enhance cooling of the mixed layer for a few hours when entrainment is occurring. This result is coincide with Dickey et al., 1998 estimated k value for hurricane Felix in the Atlantic Ocean. According to Price et al. (1994) the Rossby number is estimated as 0.052 (Table 1) for mixed layer current during Phet cyclone. Therefore, nonlocal or advective effects are likely not important during the forcing and early decay stages of Phet. The translation speed is high at box A & D and low at B & C this is one the reason for the strong cooling at box A, which means both translation speed and MSW play a vital role on upwelling.

4. CONCLUSIONS

Satellite based SST measurements divulged four areas of sea surface cooling, two to four days after the passage of Phet cyclone. Among the four areas, three areas are along and right side of the track and one is left side of the track. Maximum SST alters occurred along the track area, which is nearly 6°C. This cooling is looks like a tongue shape with three surface layers they are inner core is 25°C, outer core is 25.7°C and outer most is 26.4°C. This is a unique feature observed in the Arabian Sea since 130 years. Second strongest cooling area is also observed at the left of side of the Phet cyclone track.

The present study suggested that the surface as well as vertical variation of temperature in the cyclone generated area before and after the Phet cyclone was related to strong cyclone induced mixing/upwelling. SST cooling in and around the cyclone formed area, but it more along the track and also the MLD is much deepened as the thermocline rose and caused deep convergence. The migration of 26°C isotherm also gives a strong evidence of upwelling along the cyclone track. This cooling is continued upto three days.

Rapid negative ocean-atmosphere feedback to Severe Cyclonic Storm Phet from the large area of cooling where SSTs of 25.5 – 32°C were generated during the cyclone passage along the its track. Pre-cyclone ocean environment played a vital role in the ocean response to along track cyclone intensity changes. This gives an impression that the cyclone intensity forecasts may benefit from the inclusion more accurate location and intensity information on oceanic cyclones, the subsurface dynamics need to be studied using both insitu and coupled ocean-atmosphere models.

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